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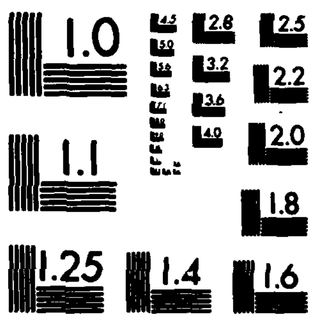

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COHERENCE BETWEEN STRATIFICATION
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S^2 is DIRECTLY PROPORTIONAL TO N2

A number of mechanisms are known to be responsible for the interdependence of stratification and shear. These include interleaving, internal waves, and instabilities such as double diffusion and breaking internal waves. In the strongly stratified seasonal thermocline the shear behaves approximately as $S^2 \propto N^2$ (Grabowski, 1980). Patterson et. al. (1981) showed that N^2 and S^2 are better correlated over vertical scales of 30 meters or more. This calculation of cross coherence between simultaneous profiles of N^2 and S^2 was intended to investigate the possibility of a limiting vertical length scale below which the correlation of N^2 and S^2 is small or zero, and above which the correlation is good. On the basis of a limited data set (9 YVETTE profiles), N^2 and S^2 appear in general to be well correlated at wavelengths larger than about 5-10 meters, except in the presence of large vertical geostrophic shear. These results offer some further evidence that levels of shear activity may be inferred from stratification at scales down to about 10 meters.

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COHERENCE BETWEEN STRATIFICATION AND SHEAR IN THE UPPER OCEAN

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September 1982

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TABLE OF CONTENTS

Section		Page
1	INTRODUCTION	1-1
2	$N^2 - S^2$ COHERENCE: METHOD OF COMPUTATION	2-1
3	RESULTS AND DISCUSSION	3-1
	REFERENCES	R-1

LIST OF FIGURES

Figure		Page
1.1	Profiles of (a) Brunt-Vaisala frequency squared, N^2; (b) vertical shear squared, S^2; and (c) $\log_{10}(Ri)$, where $Ri = N^2/S^2$, for YVETTE Station 8 in the Sargasso Sea. The vertical line in (c) is at Ri = 0.25. The dotted lines are at 135 and 250 dbars. From Patterson et al. (1981)	1-3
2.1	Positions of YVETTE Stations	2-3
3.1	Coherence amplitude and phase spectra for YVETTE Station 5. The dashed line is the level of significance at 90% confidence for coherence amplitude. 95% confidence limits on phase are $\pm 9°$	3-2
3.2	As in Figure 3.1, but for YVETTE Station 8	3-2
3.3	As in Figure 3.1, but for YVETTE Station 9	3-3
3.4	As in Figure 3.1, but for YVETTE Station 10	3-3
3.5	As in Figure 3.1, but for YVETTE Station 11	3-4
3.6	As in Figure 3.1, but for YVETTE Station 12	3-4
3.7	As in Figure 3.1, but for YVETTE Station 18	3-5
3.8	As in Figure 3.1, but for YVETTE Station 21	3-5
3.9	As in Figure 3.1, but for YVETTE Station 23	3-6

Section 1
INTRODUCTION

It has been well documented in recent years that stratification and shear in the ocean are often highly interdependent. A number of mechanisms are known to be responsible for this interdependence, including interleaving, internal waves, and instabilities such as double diffusion and breaking internal waves. For example, Eriksen (1978) documented the effects of breaking internal waves on the relationship between shear squared (S^2) and Vaisala frequency squared (N^2). His scatter plots of N^2 and S^2 computed over a vertical interval of 6.3 m show the limiting Richardson number $Ri = N^2/S^2$ to be about 1/4. Shear instability, therefore, seems to bound S^2 to values less than the local value of $4N^2$.

Eriksen's observations show that Richardson number approaches 1/4 rather infrequently. Internal waves are a possible mechanism for the apparent correlation between S^2 and N^2 when $Ri > 1/4$. Johnson and Sanford (1980) showed that an anisotropic internal wave field superimposed on a vertical temperature gradient resulted in significant coherence between vertical shear and temperature gradient. WKB scaling arguments suggest that, at least in the deep ocean, the shear due to linear internal waves behaves as

$$S^2 \propto N^3.$$

Observations made by the free-fall profiler YVETTE below the seasonal thermocline tend to support this proportionality.

In the strongly stratified seasonal thermocline, the shear behaves more nearly as

$$S^2 \propto N^2$$

(Grabowski, 1980).

The similarity between profiles of N^2 and S^2 was first pointed out by Simpson (1975). Figure 1.1 shows profiles of N^2, S^2, and Ri from the free-fall shear profiler YVETTE. In the seasonal thermocline (between the dashed lines), and to a lesser extent below the seasonal thermocline, Ri is limited by the value 1/4. The similarity between the profiles of N^2 and S^2 is immediately obvious.

In Patterson et al. (1981), we presented linear cross-correlation coefficients computed between N^2 and S^2, for different portions of an YVETTE profile. We showed that smoothing the profiles of N^2 and S^2 generally improves correlations. The implication is that N^2 and S^2 are better correlated over long vertical length scales than over short scales. This calculation led to the question of whether there is a limiting length scale, above which N^2 and S^2 are well correlated, and below which the correlation is poor. We anticipated that a calculation of coherence between N^2 and S^2 would provide a more definitive answer than simply varying the smoothing of the cross correlation. Thus we tried the coherence calculation on nine different YVETTE profiles. This technical note describes the results of that brief investigation.

In Section 2 we present an outline of the method used to compute coherence. In Section 3 we present the results and a brief discussion.

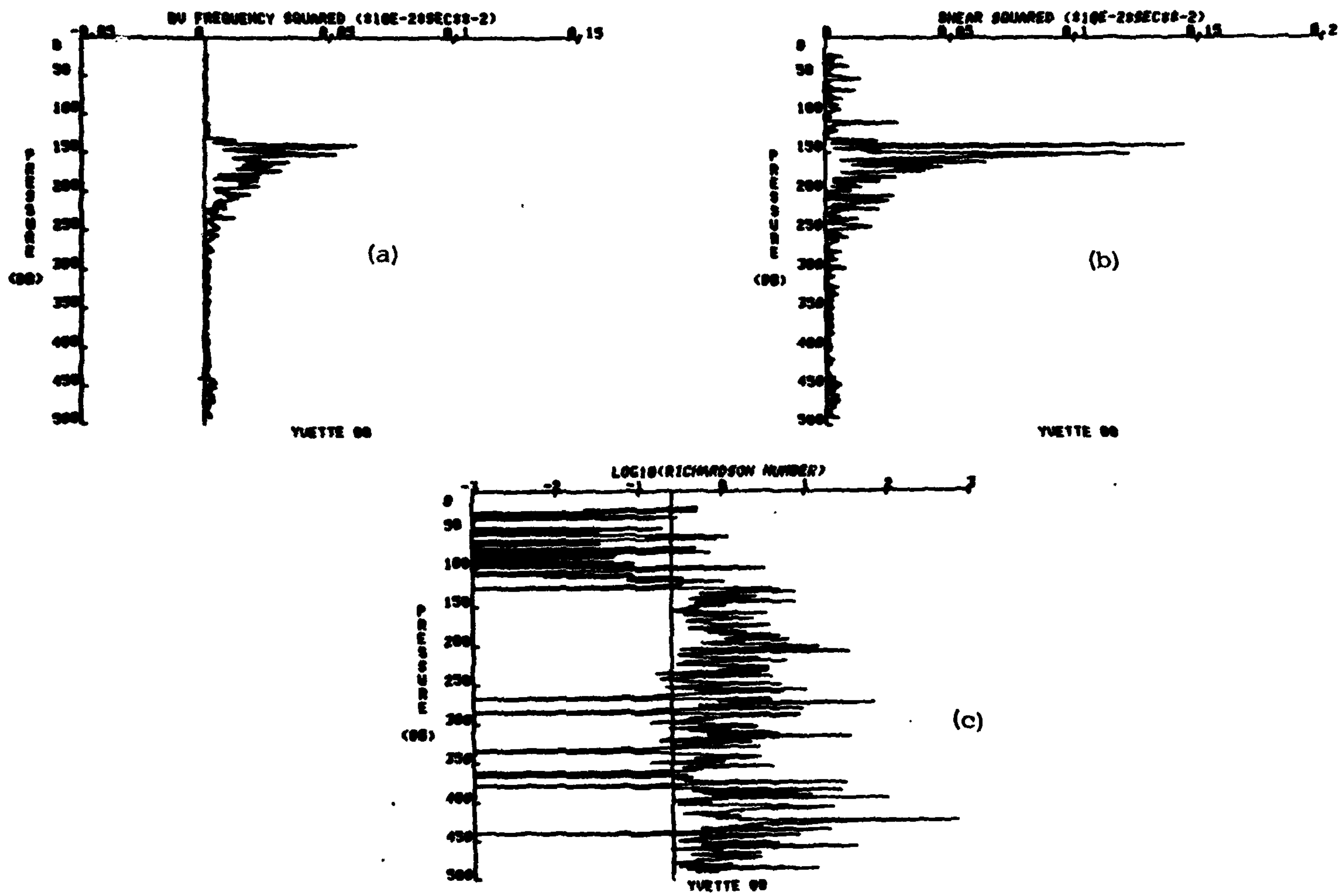

Figure 1.1 Profiles of a) Brunt-Väisälä frequency squared (N^2), b) vertical shear squared (S^2), and c) $\log_{10}$ (Ri), where Ri = N^2/S^2, for YVETTE Station 8 in the Sargasso Sea. The vertical line in c) is at Ri = 0.25. The dotted lines are at 135 and 250 meters from Patterson, et. al. (1981).

Section 2
N^2 - S^2 COHERENCE: METHOD OF COMPUTATION

The locations of the nine stations for which coherence spectra were computed are listed in Table 2.1 and shown in Figure 2.1. The data used were from the depth intervals below the mixing layer, and included both the strongly stratified seasonal thermocline and the more weakly stratified layers below. The data were sampled at approximately 1 meter intervals. Sixteen meters was chosen as the longest wavelength of interest, and thus each station was divided into records of 16 samples (approximately 16 meters) long. The number of non-overlapping 16 sample records in a given station is denoted by the integer L.

We next outline the method used for computing coherence between N^2 and S^2. Data points in the time series of N^2 and S^2 are denoted N_j^2 and S_j^2 respectively.

1. Truncate the original station data records to a length M, such that

$$M = LJ,$$

   where J is a power of two, and L is the integer defined above. We then have data records N_j and S_j where $j = 1,2,\ldots,M$.

2. Subtract the mean from each of these records.

3. Divide the station data record into 2L - 1 overlapping intervals. Apply a cosine taper

Table 2.1

YVETTE STATIONS[1]

Station Number	Time (GMT)	Date	Latitude (N)	Longitude (W)	Comment
5	1942	5 Nov. 75	32°19'	64°34'	Near Bermuda
8	0225	8 Nov. 75	35°00'	66°30'	Sargasso Sea
9	1219	"	"	"	"
10	1814	9 Nov. 75	38°09'	69°06'	Gulf Stream
11	0036	10 Nov. 75	38°05'	69°03'	"
12	1312	"	38°15'	69°07'	"
18	—	7 May 77	22°47'	70°43'	Edge of thermocline eddy
21	—	9 May 77	22°27'	70°57'	Center of thermocline eddy
23	—	16 May 77	36°24'	67°36'	Outer part of GSR[2]

1 Adapted from Lambert _et al_. (1980)

2 Gulf Stream Ring

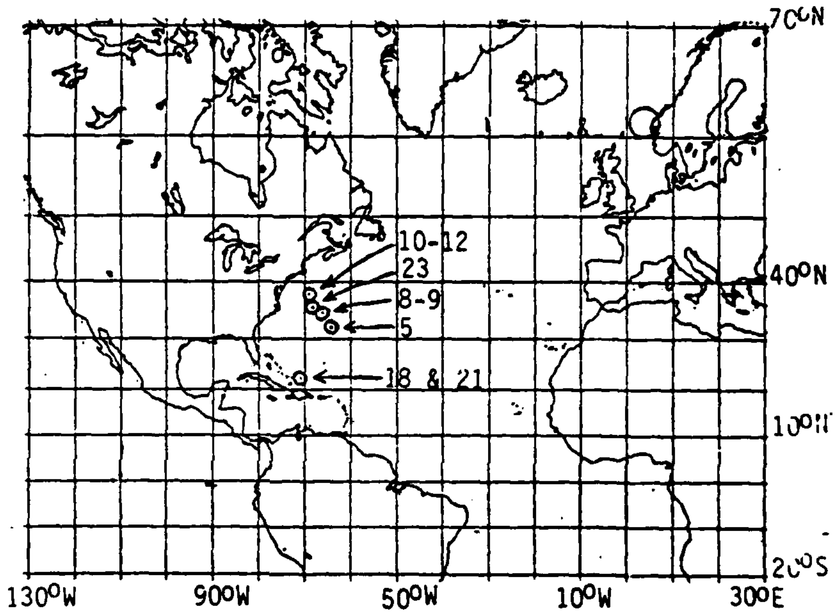

Figure 2.1. Positions of YVETTE stations

(Hanning) window to the data in each of these intervals.

4. Compute the complex valued Fast Fourier Transforms:

$$\widehat{N^2_n} = \sum_{j=0}^{J-1} N^2_j \exp\left(-i\frac{2\pi jn}{J}\right)$$

$$\widehat{S^2_n} = \sum_{j=0}^{J-1} S^2_j \exp\left(-i\frac{2\pi jn}{J}\right)$$

for each of the overlapping intervals. Here $\widehat{N^2_n}$ and $\widehat{S^2_n}$ denote spectral coefficients.

5. Compute the autospectra (G_N, G_S), cospectra (P) and quadrature spectra (Q):

$$G_N(f_n) = \frac{2h}{J} \left|\widehat{N^2_n}\right|^2$$

$$G_S(f_n) = \frac{2h}{J} \left|\widehat{S^2_n}\right|^2$$

$$P(f_n) = \frac{2h}{J} \left(\mathrm{Re}\widehat{N^2_n}\mathrm{Re}\widehat{S^2_n} + \mathrm{Im}\widehat{N^2_n}\mathrm{Im}\widehat{S^2_n}\right)$$

$$Q(f_n) = \frac{2h}{J} \left(\mathrm{Re}\widehat{N^2_n}\mathrm{Im}\widehat{S^2_n} - \mathrm{Im}\widehat{N^2_n}\mathrm{Re}\widehat{S^2_n}\right),$$

where h is the sampling interval and $f_n = \frac{n}{hJ}$ for $n = 0,1,2,\ldots,\frac{J}{2}-1$.

6. Compute the coherence amplitude and phase:

$$C(f_n) = \left[\frac{\langle P(f_n)\rangle^2 + \langle Q(f_n)\rangle^2}{\langle G_N(f_n)\rangle \; \langle G_S(f_n)\rangle}\right]^{1/2}$$

$$\phi(f_n) = \arctan\left(\frac{-\langle Q(f_n)\rangle}{\langle P(f_n)\rangle}\right),$$

where the angled brackets indicate averages over the 2L-1 autospectra, cospectra, or quadrature spectra.

When coherence is computed, an implicit assumption is made, namely, that the relationship N^2 and S^2 is linear. The coherence amplitude is a measure of the correlation between N^2 and S^2 in each frequency band.

Section 3
RESULTS AND DISCUSSION

The coherence and phase spectra for the nine stations are shown in Figures 3.1 - 3.9. Each coherence spectrum was computed with $L \sim 30$ indicating approximately 60 degrees of freedom. The level of significance at 90 percent confidence, determined according to Koopmans (1974), is denoted by a dashed line in each figure. The point at 0 cpm can be interpreted as the coherence at wavelengths of 16 m (the total record length). The range covered by this analysis is thus about 16 m to 2 m.

For all but Station 12, the phase is stable and near zero in the region of high coherence confirming that spatial fluctuations in N^2 and S^2 are synchronized at scales longer than 4-10 meters. This is consistent with the improvement in cross-correlation between N^2 and S^2 profiles reported by Patterson _et_. _al_. (1980) when the profiles were first low pass filtered with a triangular weighting function of 5 meter half-width (approximate wavelength cutoff of 10 meters).

The results are not unambiguous. Station 5 and 8 show very high coherence (~ 0.7 - 0.8) at small wavenumbers with a sharp drop at wavenumbers above about 0.2 cpm. Station 9 shows significant coherence (but with an amplitude of only about 0.4) and with a drop at wavenumbers above 0.1 cpm. Stations 5, 8, and 9 were all made in almost the same location in the central Sargasso Sea. Station 10 (in the Gulf Stream) closely resembles Station 9. However, Stations 11 and 12, also from the Gulf Stream, show insignificant

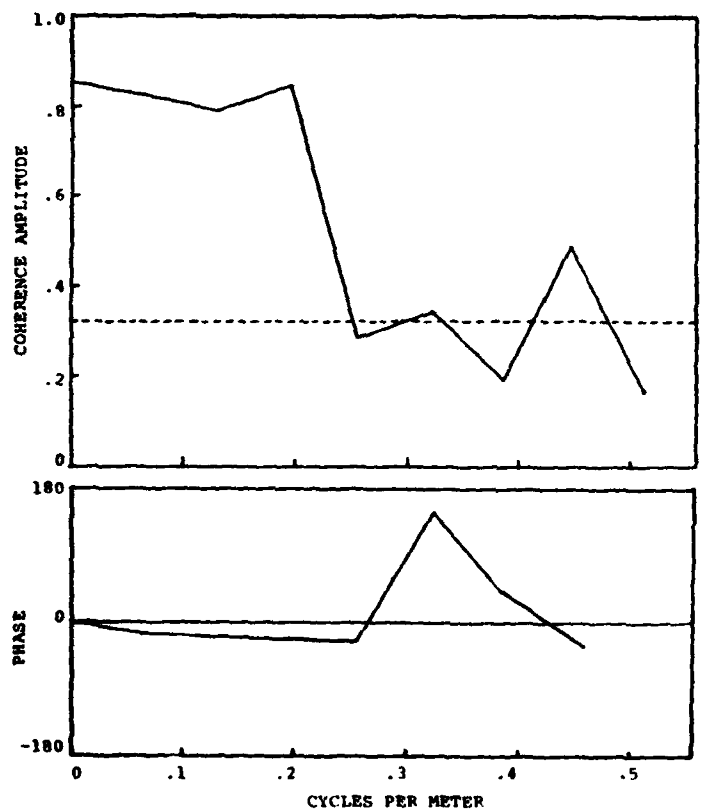

Figure 3.1 Coherence amplitude and phase spectra for YVETTE Station 5. The dashed line is the level of significance at 90% confidence for coherence amplitude. 95% confidence limits on phase are ± 9°.

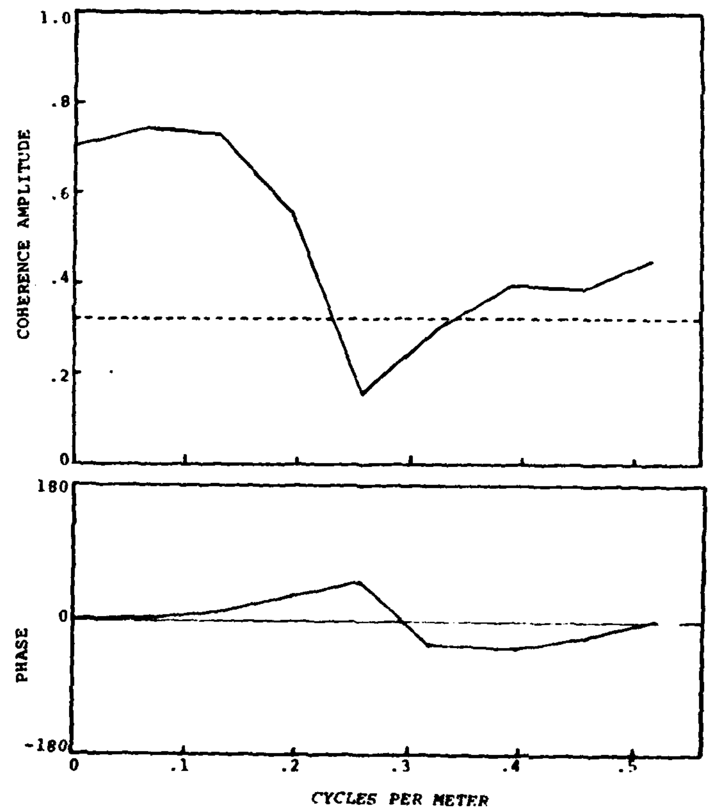

Figure 3.2 As in Figure 3.1, but for YVETTE station 8

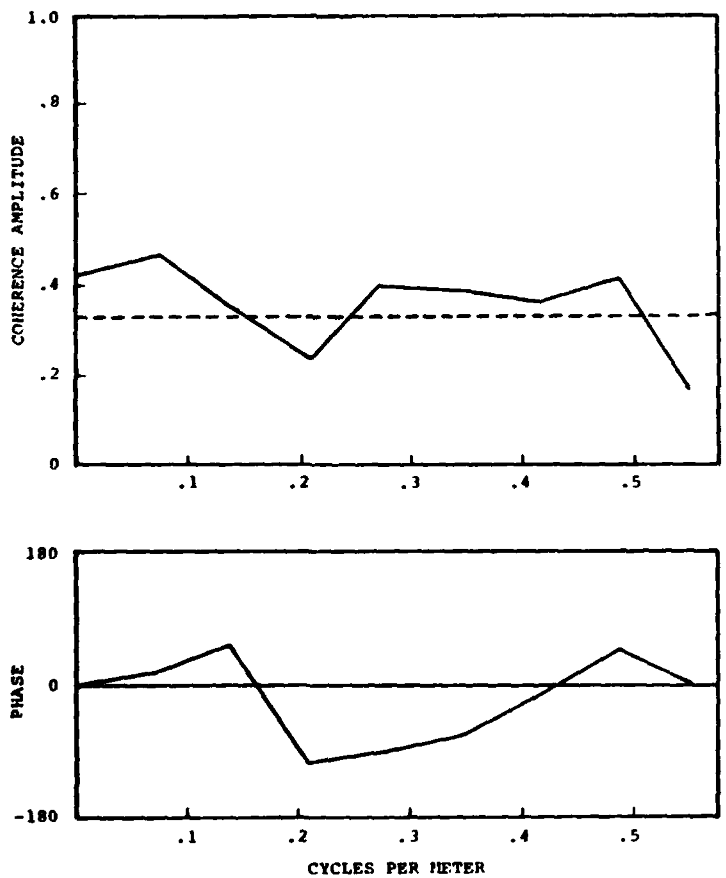

Figure 3.3 As in Figure 3.1, but for YVETTE station 9

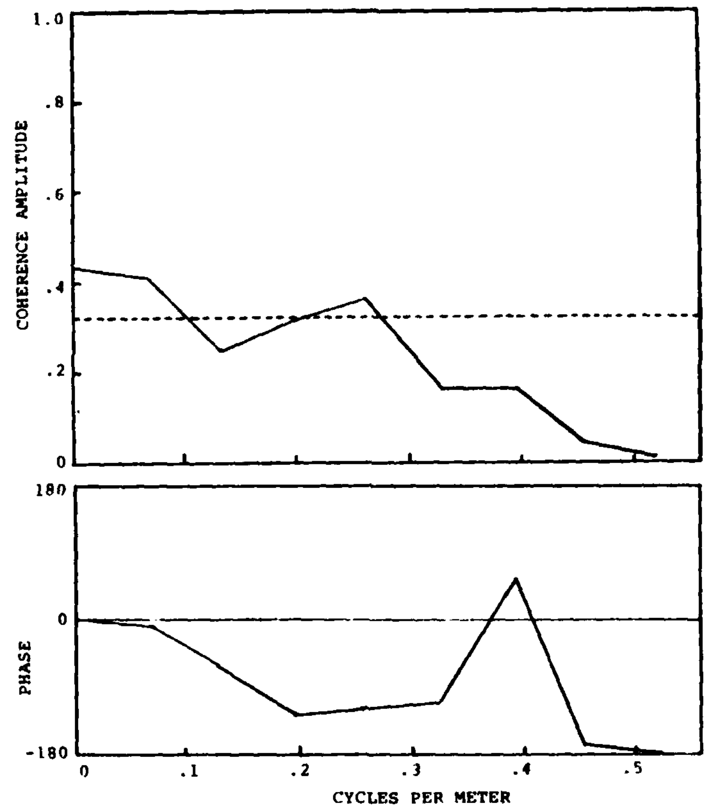

Figure 3.4 As in Figure 3.1, but for YVETTE station 10

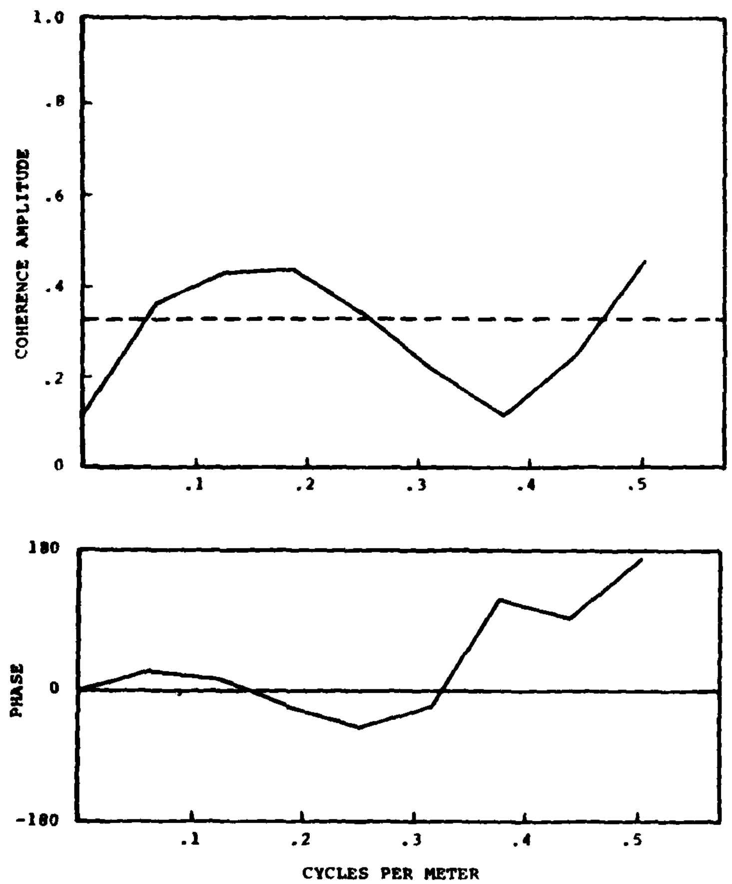

Figure 3.5 As in Figure 3.1, but for YVETTE station 11

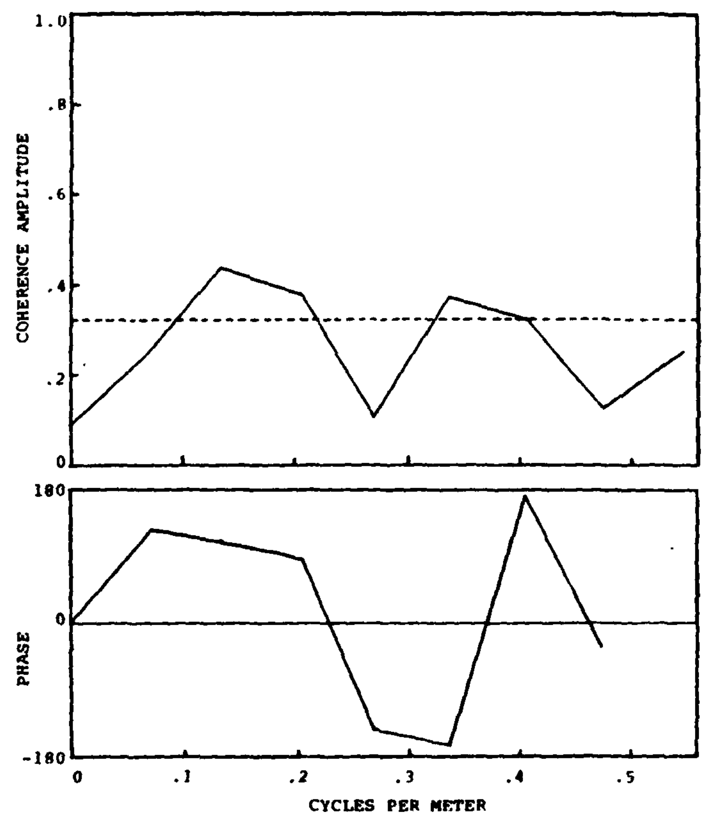

Figure 3.6 As in Figure 3.1, but for YVETTE station 12

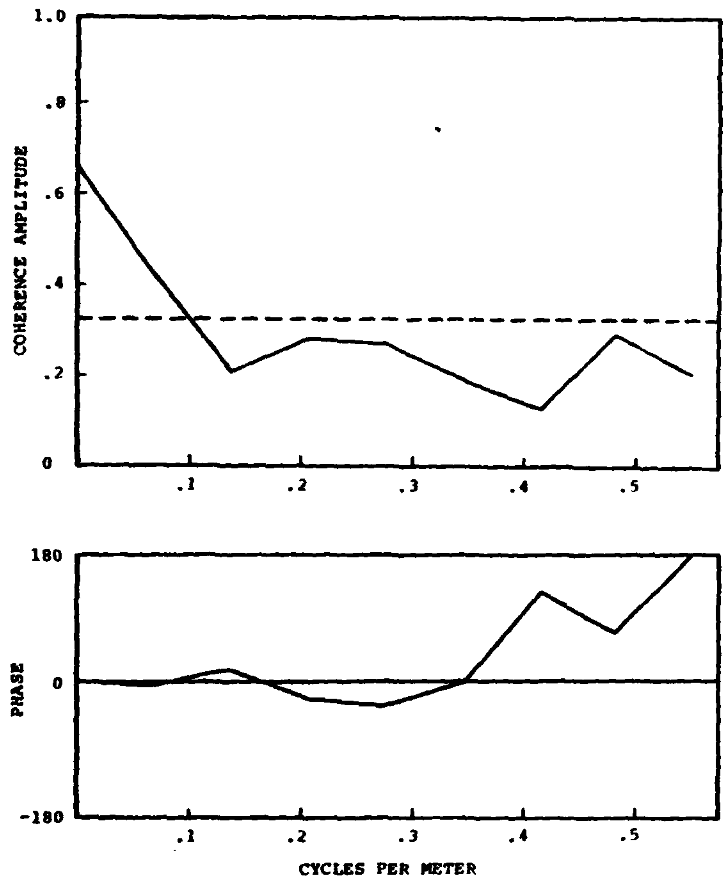

Figure 3.7 As in Figure 3.1 , but for YVETTE station 18

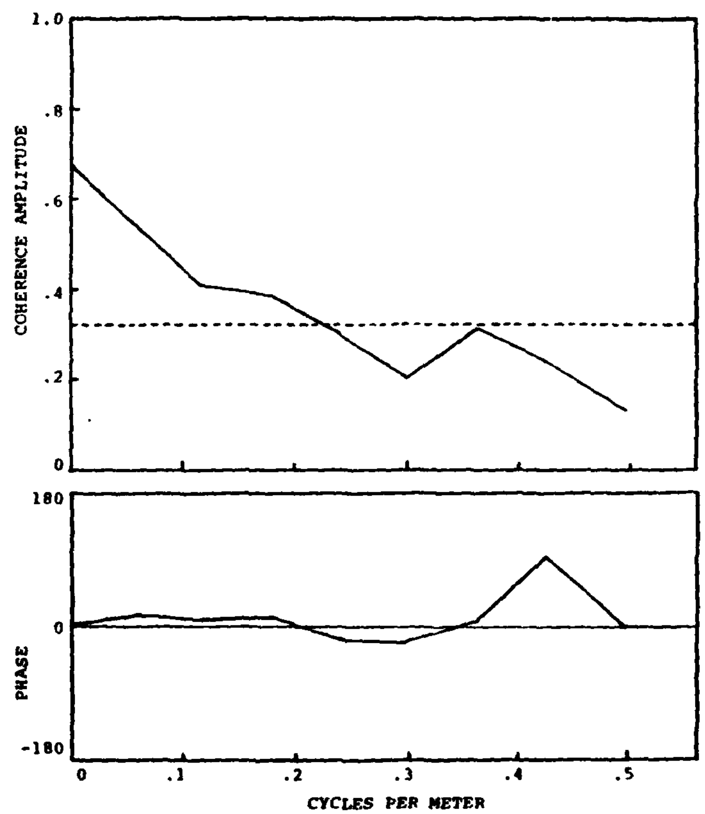

Figure 3.8 As in Figure 3.1, but for YVETTE station 21

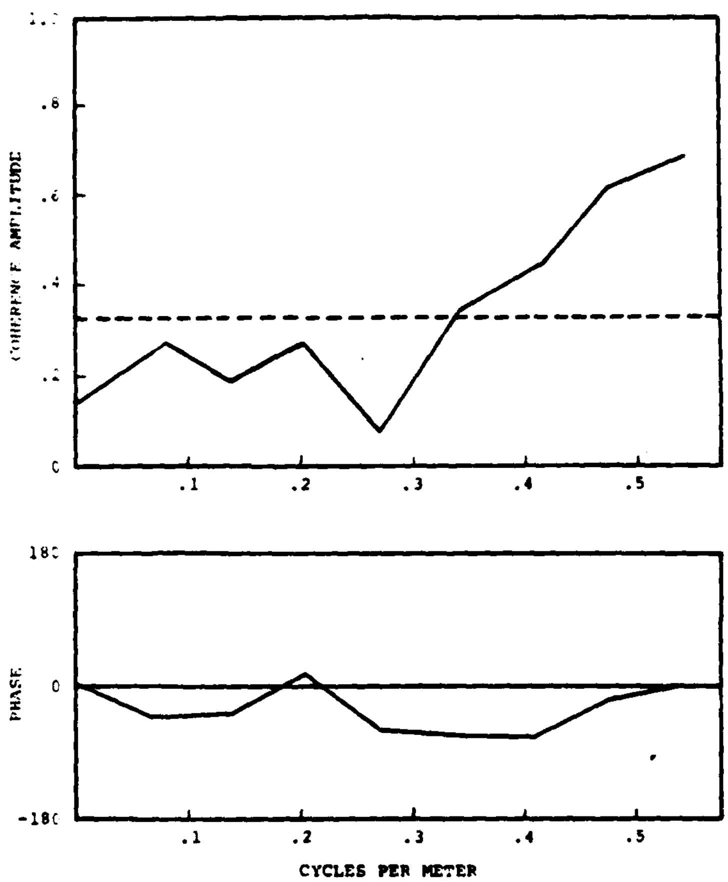

Figure 3.9 As in Figure 3.1, but for YVETTE station 23

coherence at small wavenumbers with significant coherence only between about 0.1 and 0.2 cpm, in sharp contrast with Station 10.

Stations 18 and 21 are from the same location, near the Bahamas. Both exhibit similar coherence properties, namely, moderately high coherence (0.65) at small wavenumbers, with sharp drops in coherence below 0.1 cpm (Station 18) and 0.18 cpm (Station 21). The coherence values from Station 23 (near the edge of a Gulf Stream Ring) at small wavenumbers are not significant.

There is an overall trend that suggests that small wavenumber coherence is higher in regions of relatively low geostrophic shear. However, the wavenumber above which the coherence becomes insignificant is not well-determined in any case. The best that can be said is that it occurs somewhere between 0.1 and 0.25 cpm.

In summary, on the basis of analysis of a very few profiles, N^2 and S^2 appear in general to be well correlated at wavenumbers smaller than about 0.1-0.2 cpm, except in the presence of large vertical geostrophic shear. Profiles obtained in regions of large vertical geostrophic shear show no significant coherence at the smallest wavenumbers addressed in this analysis (~ 0.06 cpm). In contrast, the results of Patterson et. al. (1980) suggest that such profiles (e.g., Station 12) are well correlated at longer wavelengths (smaller wavenumbers). One station (Station 10), obtained in the Gulf Stream, does exhibit coherence, in the present analysis, at wavelengths of 16 meters and is thus an exception. These results do offer some further evidence that levels of shear activity may be inferred from stratification at scales down to about 10 meters.

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